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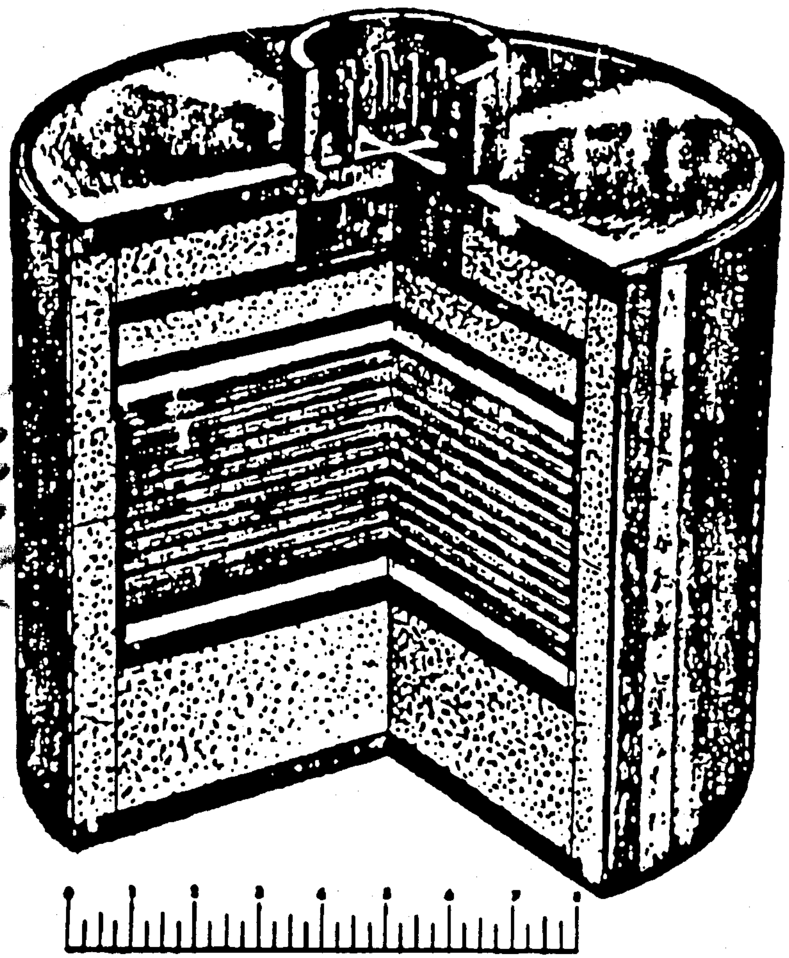

THERMAL INSULATION (Min-K)

HEAT SOURCE ($Fe+KClO_4$)

HEAT OF FUSION HEAT SINK ($NaCl-Li_2\ SO_4$)

CALCIUM ANODE

DEB
DEPOLARIZER ($CaCrO_4$)
ELECTROLYTE (LiCl, KCl)
BINDER (SiO_2)

HEAT PAPER ($Zr+BaCrO_4$)

THERMALLY ACTIVATED BATTERY

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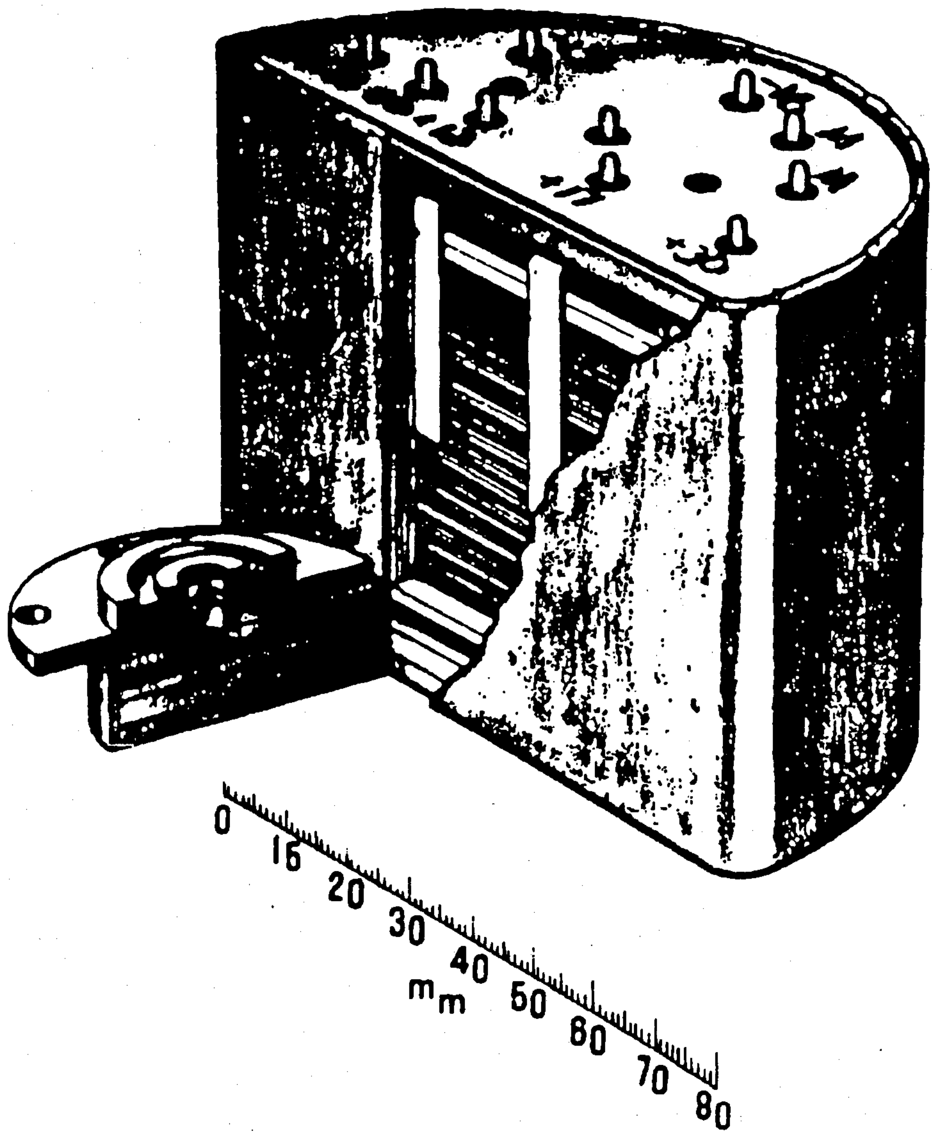
MC2936 THERMAL BATTERY



DEPOLARIZER-ELECTROLYTE-BINDER (DEB)

HEAT PELLET & INTER CELL CONNECTOR (Fe-KCl O_4)

NEGATIVE ELECTRODE (Ca)

HEAT PAPER

UNCLASSIFIED

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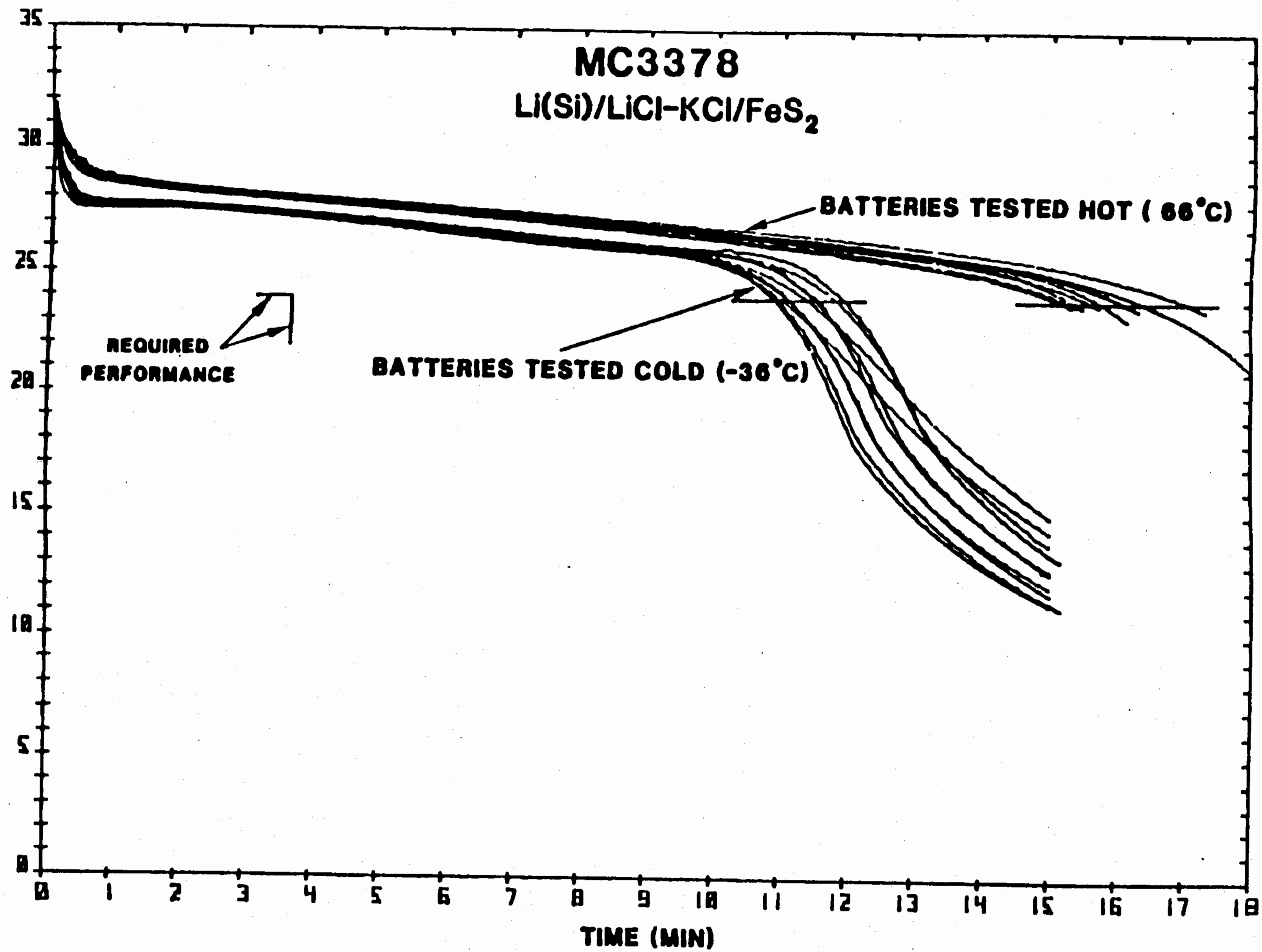
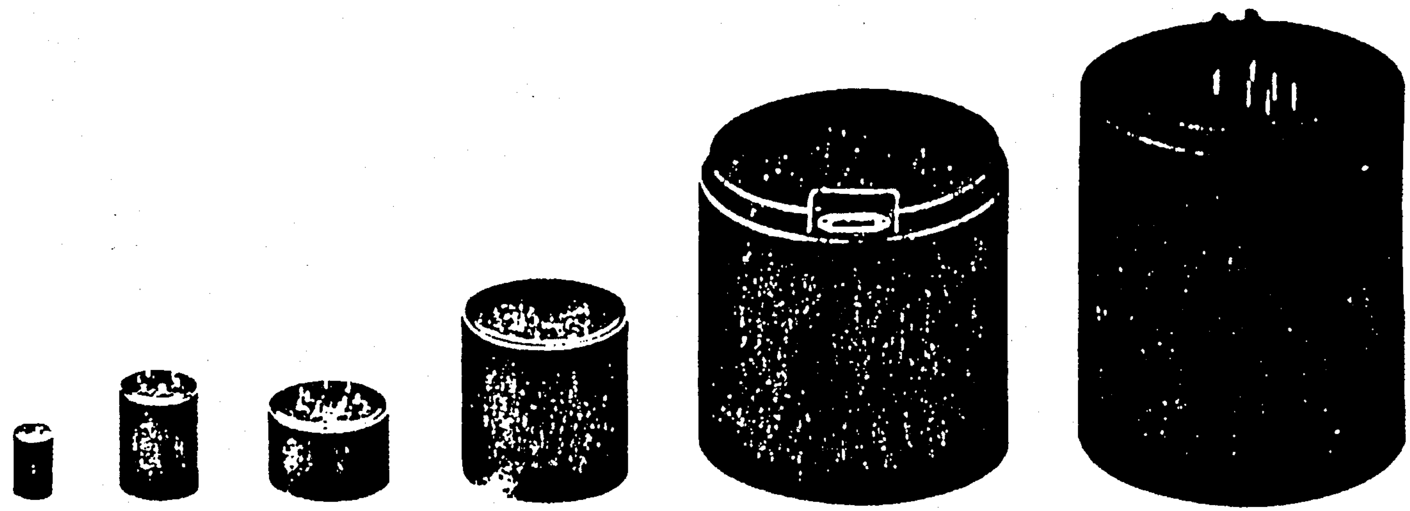

MC3378
Li(Si)/LiCl-KCl/FeS2
BATTERIES TESTED HOT (66°C)
BATTERIES TESTED COLD (-36°C)
REQUIRED
PERFORMANCE
35
30
25
20
15
10
5
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
TIME (MIN)

$Li(Si)/FeS_2$ SYSTEM BATTERIES



PULSE	SPIN	MULTIVOLTAGE	LONGLIFE	INSTRUMENTATION	HIGH CURRENT
fast rise 40 amps for 600 mst	operates at 18,000 rpm	5 voltages over a 5.1 current density range	.35 amps for 1 hour in 400 cm^3 volume	3.2 amps for 1½ hours	30 amps for 30 minutes

A REVIEW OF THERMAL BATTERY TECHNOLOGY

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Albuquerque, New Mexico

ABSTRACT

This report reviews the evolution of thermal battery technology from World War II to the present. It discusses the first applied work with thermal cells, the transfer of this laboratory technology to the United States, the development of the initial cup technology by the U. S., and the evolution of this technology to the later pellet technology. The paper by F. Tepper will then discuss the performance of thermal batteries and compare this performance with that of other ordnance batteries.

INTRODUCTION

The electrochemical power sources used in nuclear weapons to date have been lead-acid, nickel-cadmium, silver-zinc, and thermal batteries. The lead-acid battery was used in the first atomic bomb and in later weapon systems until 1953, when it was replaced by the nickel-cadmium battery, followed shortly by the silver-zinc battery. These aqueous electrolyte batteries all had a critical deficiency: their wet stand time was so short that either the battery had to be frequently recharged or the electrolyte had to be carried separately and injected into the battery just before its use. The thermally activated battery, introduced in 1955, solved the wet stand problem. Since then, it has been the sole power source used by Sandia Laboratories for nuclear weapon systems.

The thermal battery is so called because it contains a pyrotechnic heat source that, when ignited, thermally activates the battery by melting the electrolyte, which is a salt mixture. Salt mixtures are solid and chemically inert at room temperature, but when fused become fluid and highly conductive. These properties of the electrolyte provide the long shelf life and good electrical performance of the thermal battery (1,2).

The origin of the thermal battery dates back to World War II when Dr. Ing. Georg Otto Erb, working in Germany, developed the first practical cells, using a salt mixture as an electrolyte. Dr. Erb investigated the performance of several couples and electrolytes, the effects of salts with water of hydration, and the effects of water in unhydrated electrolyte salts. He also conceived and developed batteries for several ordnance applications, including the V-I and V-II rockets and artillery fusing systems; however, none of these batteries was produced for field use. Dr. Erb was interrogated by British Intelligence at the end of the war and his studies were reported to them in a paper entitled "The Theory and Practice of Thermal Cells" (3,4). This information was conveyed by the British, and possibly through other channels, to the United States Ordnance Development Division of the National Bureau of Standards, which later became Harry Diamond Laboratories (HDL). In this paper the authors will discuss only the channel for which documentation is presently available.

Prior to August 1946 (5) Mr. Grenville Ellis, U. S. Signal Corps (now the U. S. Army Electronics Command) brought copies of Dr. Erb's report to a meeting of the Joint Battery Advisory Committee. This committee of about ten people representing the Navy, Army, Air Force, and Industry met informally to exchange ordnance battery information. Dr. A. G. Hellfritzsch, of the Naval Ordnance Laboratory and a member of this committee, recognized the relevance of Dr. Erb's work to the battery needs of the VT (Variable Time) Fuze Panel under the National Research and Development Board. Dr. Hellfritzsch conveyed this report to Roger W. Curtis, who was chairman of the VT Fuze Panel and was also in the Ordnance Development Division of the National Bureau of Standards (6). Within a few weeks Curtis and his co-workers had demonstrated the capabilities of thermal cells for ordnance applications. Combining this with the work under contract to Catalyst Research Corporation to develop gasless pyrotechnics, they developed a self-contained thermal battery (6).

In the late forties the Wurlitzer Corporation began production of HDL's first thermal battery. This battery was used in a mortar round and the total production reached over a million batteries (7).

In 1952 Curtis reported on thermal battery technology at a symposium attended by various ordnance groups (8). Because of its desirable ordnance characteristics, the thermal battery system was adopted by the military for ordnance applications and by the U. S. AEC for nuclear weapon systems.

The early thermal battery designs are frequently referred to as "cup," "pad," "cup and cover," "closed-cup," and "conventional" batteries. These early batteries had three distinguishing characteristics: heat-paper pads, electrolyte and depolarizer pads, and intercell electrical connectors, which are discussed in more detail later. These three characteristics distinguish the earlier batteries from the later pellet-type batteries which use heat powder pellets, electrolyte-depolarizer pellets, and no intercell connectors. The evolution from the earlier batteries to the present pellet-type batteries was gradual, and there were several hybrid batteries which included both technologies, such as the Naval Ordnance Laboratory/Eureka-Williams battery which was the first to use a pellet.

This review describes the early cup technology (9,10,11), one of the later hybrid systems (2,10,12), and the present pellet technology (11,13,14). Performance characteristics of the thermal battery are discussed with reference to the Ca/LiCl-KCl/$CaCrO_4$ electrochemical system and the pellet technology which is the principal system used by this Laboratory. Discussion of other electrochemical systems and references to these systems are given by Jennings (15).

THE CUP TECHNOLOGY

Figure 1 shows the typical structure of a single cell in the cup design. In the cell are the anode, the electrolyte pads, the depolarizer pads, the cup in which these are enclosed, and a heat pad to thermally activate the cell.

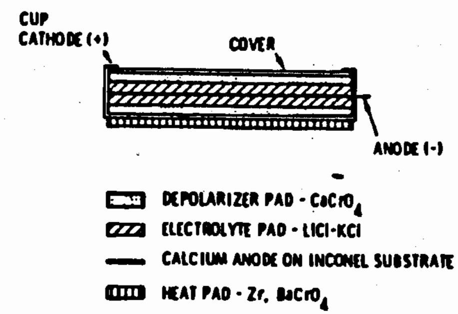

Fig. 1. - Single thermal cell - cup technology

The anode consists of calcium affixed to both sides of a metallic substrate[1] that serves both as the anode current collector and as the negative terminal by virtue of a tab extending through a slit in the side of the cell case. Although not shown in the figure, the anode is electrically insulated from the cathode cup.

The electrolyte pads are adjacent to the calcium surfaces and contain the electrolyte, the eutectic mixture of the lithium-chloride/potassium-chloride system (59 mole % LiCl-41 mole % KCl), which has a melting point of 352 C. The pads are formed by passing a fiberglass tape through a vat of molten electrolyte and punching pads from the tape after it has cooled and the electrolyte has solidified.

The depolarizer[2] pads, adjacent to the electrolyte pads, complete the active cell stack. These pads are punched from a paper-like sheet formed by pressing and drying a slurry containing the calcium chromate depolarizer along with glass and ceramic fibers.

The active cell stack is then placed in a metallic cup, covered with a metallic disc, and the sides of the cup are crimped over the disc as a seal. The cup and disc thus hold the cell components in place and serve as the cathode current collector and positive terminal of the cell.

The last component of the single cell is the heat pad, which activates the cell by raising its temperature to the operating range of 500 to 600 C. The pad is punched from heat paper sheets formed by a process similar to that used for the depolarizer pads, but involving a slurry containing zirconium fuel and barium-chromate oxidizer instead of the depolarizer. (The slurry also contained asbestos fibers. Later, Sandia eliminated the asbestos because it releases water of hydration when heated.)

For simplicity, only the basic components of the cup cell have been described. When one includes intercell connecting tabs, wire-mesh current collectors, electrical insulators, etc., there can be as many as 27 individual parts in a cup cell as compared to the 3 parts of the later pellet cells.

It should also be noted that with the cup technology, as well as with the pellet technology, most of the battery materials either absorb or react with water, particularly the electrolyte which is very hygroscopic. Since battery performance is severely degraded if the components are exposed to water vapor concentrations greater than 1500 ppm[3], all processes are carried out in dry rooms. At this Laboratory for example, the dry rooms are maintained at less than 300 ppm; and in addition, all battery components are vacuum dried at 100 C prior to assembly.

Figure 2 illustrates thermal battery construction using the single cell described above. The active battery stack is formed by first welding the appropriate number of cells together, the negative tab of one to the positive case of the next, and then inserting a heat pad between each pair of cells to heat them and to insulate them from each other electrically. Electrical leads are attached and a narrow fuse strip of heat paper is laid up the side of the stack and across the top cell. The stack is then capped on each end

---

1. Inconel, iron, stainless steel, and nickel are the metals most often used.

2. Depolarizer is an historic battery term used to identify the active cathode material which is reduced electrochemically during battery discharge.

3. At 25 C, 1500 ppm is 5% relative humidity.

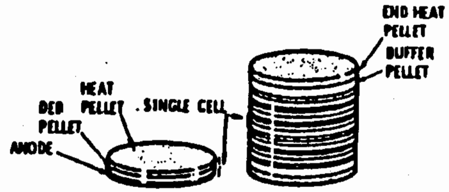

Fig. 5. - Single cell and battery stack - pellet technology

lithium-sulfate/sodium-chloride eutectic, which melts at 493 C and has a heat-of-fusion of about 84 calories per gram. Part of the heat from the end heat pellets is used to melt the eutectic salt in the buffer pellet. When the end of the battery stack cools to 493 C, the eutectic solidifies and releases its heat-of-fusion to maintain the battery temperature for a longer time.

As shown in Figure 6, the assembly of a pellet thermal battery is completed with the addition of electrical leads, match, fuse train, insulation, and battery case. The thermal insulation used is Fiberfrax for regular applications and Johns-Manville's Min-K 2002 for long-life applications. The Min-K 2002 was originally developed under AEC contract for thermoelectric generators and selected for thermal batteries after an extensive evaluation program (13,14). It is composed of silica, quartz fibers, and titanium dioxide.

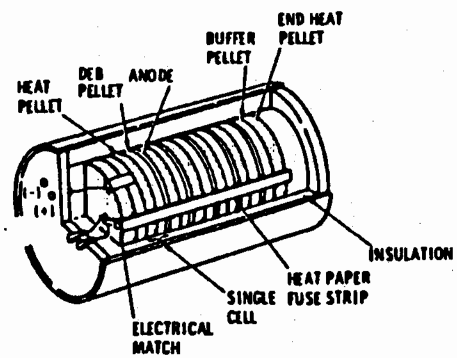

Fig. 6 - Thermal battery construction - pellet technology

Figure 7 shows the steps of battery construction and the use of center bolt construction to ensure concentricity of the lots. In this construction, a quartz-covered steel bolt is passed through center holes in the battery stack and two steel end plates. The result is a concentric, integral, rugged subassembly that can be easily handled and inspected.

Fig. 7 - Thermal battery - pellet technology

The pellet battery offers several improvements over the cup battery: longer activated life, more reproducible performance, greater ruggedness, no intercell connectors, lighter battery cases, better control of materials and processing, simplified fabrication, reduction of inspection and testing, elimination of hazardous heat pads, and lower cost. In addition, the pellet battery design is simpler and thus more amenable to investigation. This in turn has led to improved performance and further advancements, particularly with respect to longer life. Production has been completed on a thermal battery having an activated life of 15 minutes (21) and exploratory thermal batteries under development at Sandia have demonstrated activated lives of over 60 minutes (22).

ACKNOWLEDGEMENTS

The authors acknowledge the assistance of the individuals who provided much of the information concerning the early history of thermal batteries: A. Attewell of the Royal Air Force Establishment in the British Ministry of Defense, E. V. Foreman and C. W. Jennings of Sandia Laboratories, B. Kaplan of Harry Diamond Laboratories, R. T. Mead of Wilson Greatbatch, Ltd., R. D. Walker of the University of Florida, I. D. Yalom of the Naval Ordnance Laboratory, and particularly A. G. Hellfritzsch of the Naval Ordnance Laboratory.

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The Energy Stored in the Systems

$$E = \frac{CV^2}{2} = \frac{Q^2}{2C} \qquad E = \frac{LI^2}{2} = \frac{\phi^2}{2L}$$

With Q and ϕ Constant, We Gain Energy, If

$$C = \frac{\varepsilon A}{D} \qquad L = \frac{uA}{D}$$

Are Decreased By:

Pulling Plates Apart (Van de Graph)	Pushing Wires Apart
Pulling Dielectric Out	Pulling Core Out
Decreasing Dielectric Constant by Lattice	Continuously Shorting Out Turns (Wire Coil Flux Compressor)
Destruction (Ferroelectric Pulse Generator)	Collapsing System (General Flux Compression)

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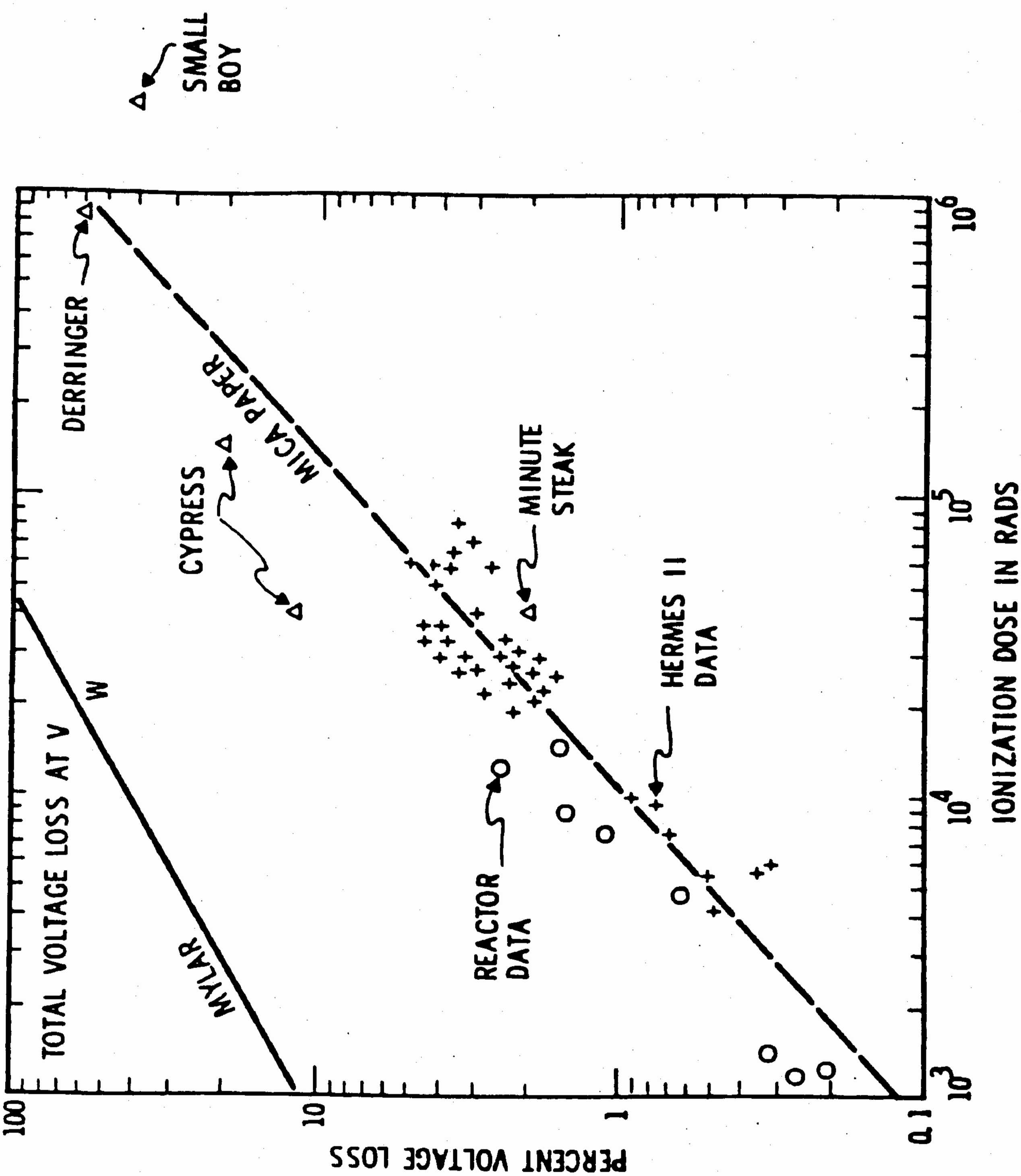

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NEUTRON MULTIPLICATION RATE

$$\frac{dN}{dt} = \frac{XN}{T}$$

$$\frac{dN}{dt} = \alpha N$$

$$N = N_0 e^{\alpha t}$$

$\alpha < 0$ subcritical

$\alpha = 0$ critical

$\alpha > 0$ supercritical

N = number of neutrons

X = excess number of neutrons per fission
(0.5 - 1.0 assumed to equal **1.0)**

T = time per fission generation
(10^{-8} sec)

= multiplication rate
(10^{8} generations/sec)

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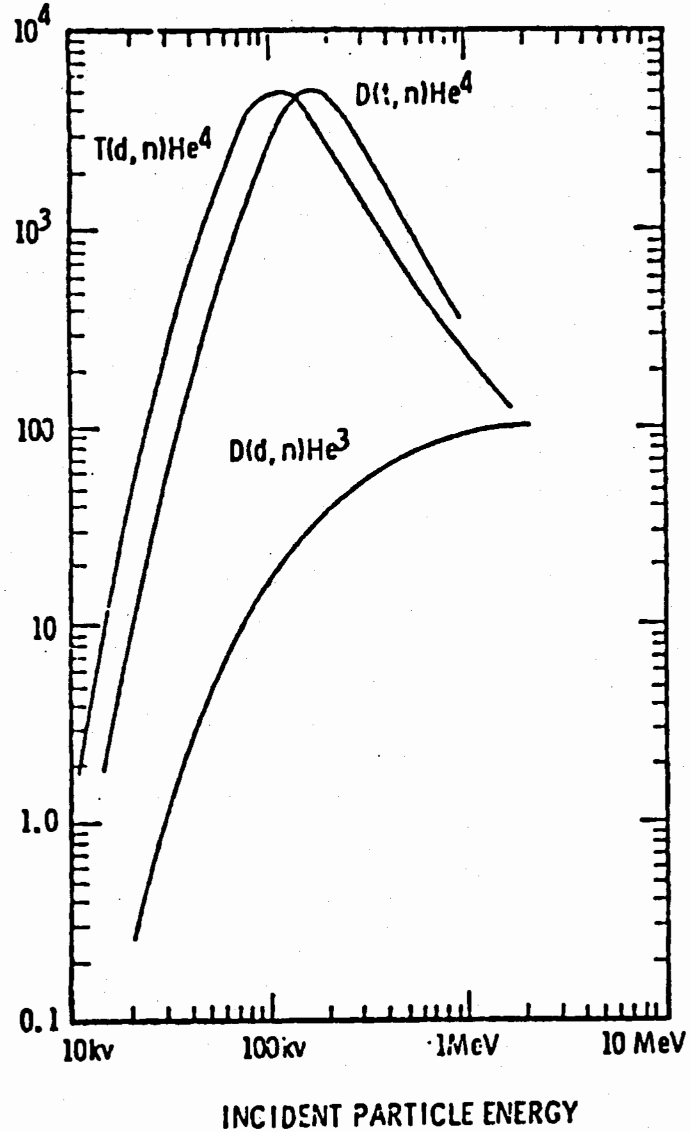

Figure 1. Reaction Cross Section Versus Incident Particle Energy

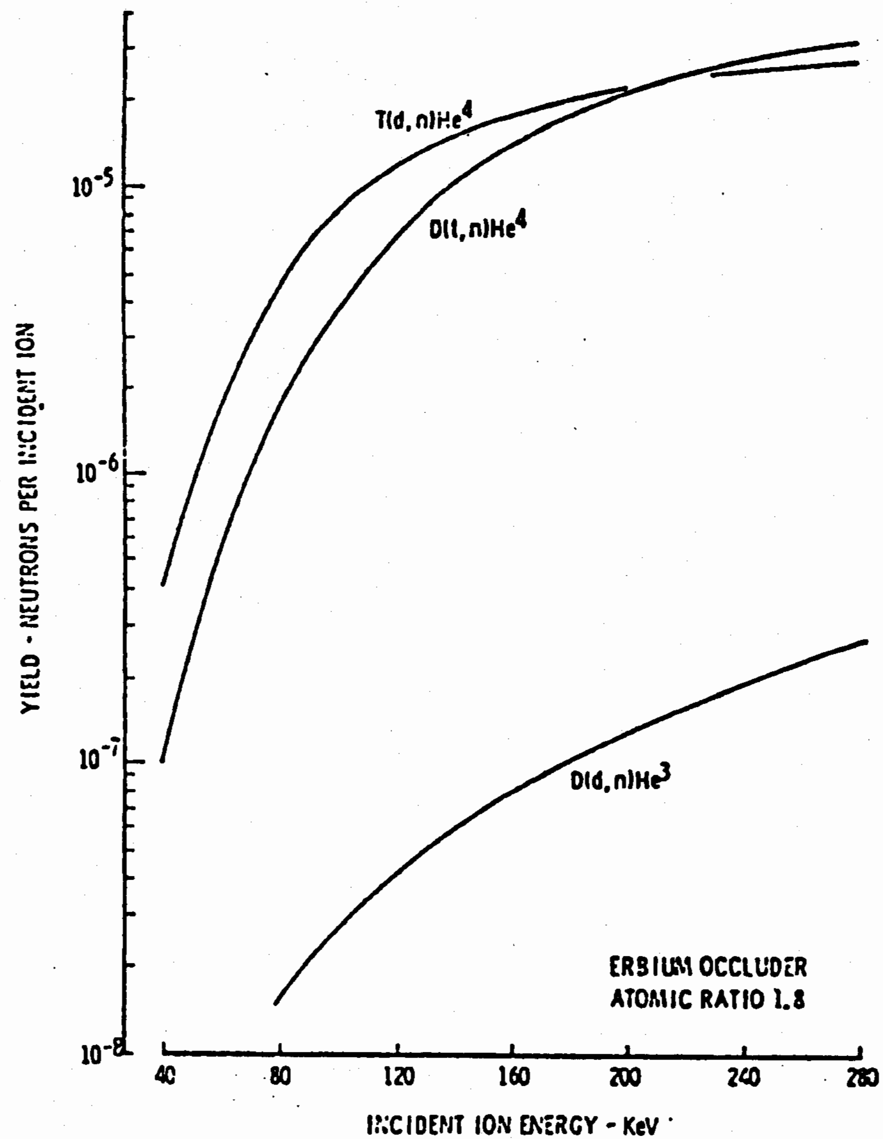

Figure 2. Theoretical Thick Target Yield

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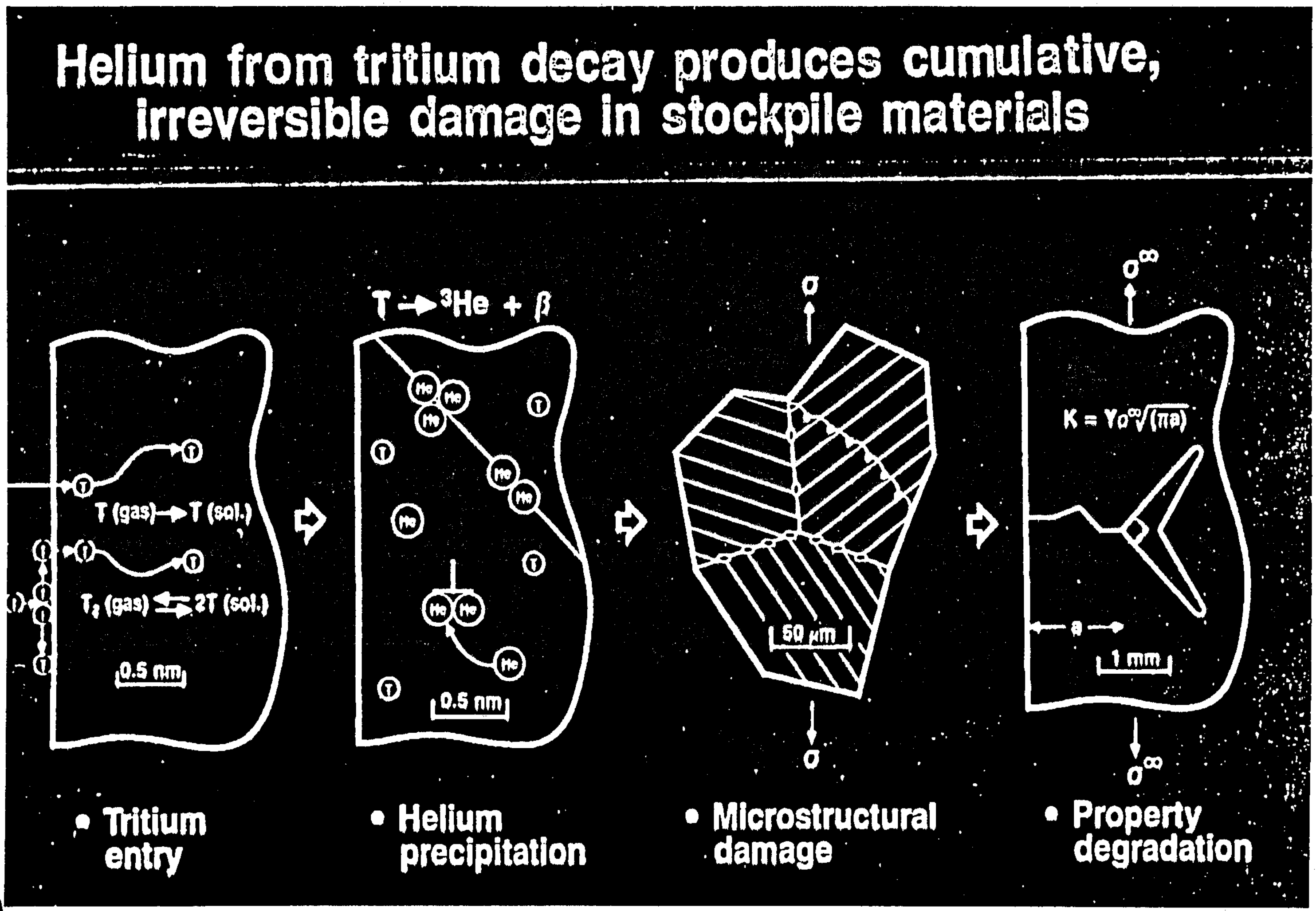

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Nonproliferation Initiative

What Constitutes a Weapon of Mass Destruction

- Indiscriminate nature of use
- Effect not confined to Belligerents
- Excessive injury -- "cruel and unusual"
- Inability to defend against effectively
- Use would overwhelm medical and evacuation resources
- Notion of "terror"

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ARMS CONTROL IN THE ANCIENT WORLD

1269 BC	Earliest known peace treaty (Egypt and the Hittites), cemented by the marriage of Ramses II to a Hittite princess.
1100 BC	Philistines restrict the use of iron by the Israelites (1 Samuel 13:19-20).
700-800 BC	"...and they shall beat their swords into plowshares..neither shall they make war anymore" (Isaiah 2:2-4).
546 BC	Following the first recorded arms control conference, a "cessation of armaments" ends 72 years of hostilities in the Yangtse River Valley in Honan Province, China.

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ARMS CONTROL IN THE ANCIENT WORLD (CONT'D)

400-500 BC	Athens and Sparta agree to dismantle fortifications although during the negotiations the Athenians hedged their bet by continuing to build their ramparts "high enough to be defended" (Peloponnesian War, Thucydides). Note that, according to the Aristophanes, the women of Athens and Sparta, under the leadership of Lysistrata, tried a different approach to forcing an end to hostilities!
450 BC	Socrates to Glaucon -- no use of poisoned weapons or poisoned water (The Republic, Plato).
300-400 BC	No weapons concealed in wood, no barbed or poisoned points, no points "blazing with fire" (India's Book of Man).
202 BC	After the battle of Zama, Carthage is required to surrender all war elephants and all but 10 triremes to Rome (Book XXX, Livy).

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The Changing Context

Old	New
Bipolar Rigidity	Multipolar Complexity
Predictable	Uncertain
Communism	Nationalism/Religious Extremists
U.S. Dominant Western Power	U.S. Militarily No.1 - Not Economical
Fixed Alliances	Ad Hoc Coalitions
"Good Guys and Bad Guys"	"Grey Guys"
U.N. Paralyzed	U.N. Viable

Ref.: National Security in the 1990s: Defining a New Basis for U.S. Military Forces, Rep. Les Aspin, Chrmn House Armed Services Committee, January 6, 1992

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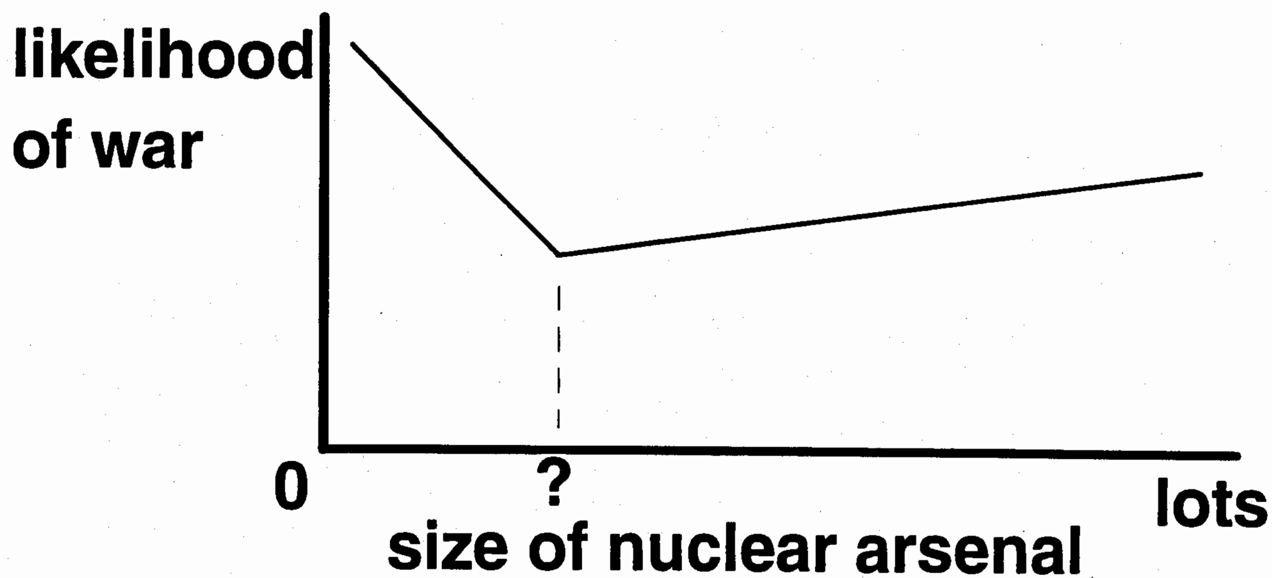
Nonproliferation Initiative

Why Not Zero?

Many nations and individuals want us to completely eliminate weapons -- attractive philosophy but dubious policy:



There may be things worse than nuclear weapons (e.g. biologics)

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